MODELING AND SIMULATION OF A BUCK CONVERTER
CONTROLLED A SENSORLESS DC SERIES MOTOR

Bassim M.H. Jassim & Tagreed M. Ali
University of Baghdad, college of Eng., electrical Eng. Dept.

ABSTRACT
This paper presents modeling and simulation of a speed sensorless control for dc series motor driven by a buck converter through computation of the motor speed from converter output voltage and current. The system model considers the nonlinearity of the series motor magnetization characteristics including the variation of the field inductance with the motor current.

الخلاصة:
يقدم البحث نمذجة ومحاكاة محرك تيار مستمر متوازي الاتجاه معزى من محول تيار مستمر خفيف للفولتيات وسيطر على سرعته بدون استخدام متحسس سرعة. نمذجة المحرك تأخذ بنظر الاعتبار الأطراف الالتحاث للكهرباء التربائي للمحرك محتضنة تغير معامل الحث الذاتي لمجات الاتجاه المتوازي مع تغير التيار.

KEY WORDS: DC series motor, speed control, sensorless.

List of Symbols:
e_g : Motor generated voltage (or back emf).
f_s : Converter switching frequency.
i_a : Motor armature current.
i_L : Converter inductor current.
i_o : Converter output current.
K_p : Controller proportional constant.
n : Motor speed.
n_o : Motor speed corresponding to that of E_g versus I_a curve.
n_ref : Motor reference speed.
T_d : Developed torque.
v_a : Motor armature voltage.
v_c : Converter capacitor voltage.
\( v_o \): Converter output voltage.
\( B \): Friction coefficient.
\( C \): Converter capacitance.
\( D \): Duty ratio.
\( E_g \): Average motor generated voltage.
\( I_a \): Average armature current.
\( J \): Moment of inertia.
\( K_{a\Phi} \): Back emf and torque constant.
\( L \): Converter inductance.
\( L_a \): Motor armature circuit inductance.
\( L_f \): Series field inductance.
\( R_a \): Motor armature circuit resistance.
\( R_f \): Series field resistance.
\( R_{CSR} \): Capacitor equivalent series resistance.
\( R_l \): Converter inductor internal resistance.
\( T_d \): Motor developed torque.
\( T_i \): Controller integral constant.
\( T_l \): Load torque.
\( T_s \): Switching time period
\( V_a \): Average motor armature voltage.
\( V_c \): Average capacitor voltage.
\( V_o \): Average converter output voltage.
\( V_s \): Converter input voltage.
\( \Delta i_L \): Converter inductor current ripple.
\( \Phi \): Flux linkage in the field in Wb-turn.
\( \psi \): Flux in Wb.

**INTRODUCTION**

DC series motor are extensively used in traction and application which required high starting torque[Seen]. Its speed can be controlled by varying the armature voltage using dc-dc converter operated in high switching frequency to supply continuous armature current without significant torque and speed ripple. There are many articles study the modeling of the dc series motor, some of them like [Okoro 08] and [Soliman 95] ignores all the nonlinearity of the magnetization characteristics while [Samir 98] take its effect on the back emf and the developed torque, but consider the inductance of the series field is constant.

In much application the use of speed sensors like tachogenerator or shaft encoder will add a significant cost and weight to the drive system. In this work, these adverse effects can be avoided using a sensorless speed control. The first section of this work demonstrates the design, modeling and simulation of the buck converter, while section two explains the dc series motor modeling and simulation. The speed computing unit, the PI controller will explained in section four and five respectively. The system performance is evaluated using Matlab Simulink toolbox through demonstrating the transient response of the motor speed and current due to step change in the
desired speed, load torque, and the input voltage. The block diagram of the proposed system is shown in Fig.1, where the output voltage of the buck converter is applied to the dc series motor. The motor armature voltage and hence its speed is controlled by using a pulse width technique to control the power MOSFET. The reference speed signal which represents the required motor speed is compared with the actual speed which is computed from the measurement of the armature voltage and current. Any disturbance in the motor load torque or converter input voltage or change in the reference speed causes the PI controller to produce an adequate control signal which is then compared with a constant frequency sawtooth waveform to adjust the duty ratio of the gate control pulses to maintain the motor actual speed equal to the reference speed.

-The buck converter design, modeling and simulation:
The buck converter steady state output voltage depends linearly on the duty ratio \( D \) which is defined as the ratio of the on duration to the switching time period. The converter output voltage is given by:

\[
V_a = DV_s, \quad 0 \leq D \leq 1
\]  

(1)

The buck converter modes of operation are explained in details by [Mohan 03].
The converter switching frequency is 20 KHz, and the input voltage is 240V.

Inductor design:
The inductor value depends on the admissible current ripple \( \Delta i_L \) which is given by the following relation [Mohan 03]:

\[
\Delta i_L = \frac{1}{L} (V_s - V_a) \cdot \frac{D}{f_s}
\]

(2)

The continuous conduction mode of the converter is ensured by making the minimum output current equal to the minimum permissible motor current which is taken to be 1A according to the specifications of the used motor in this work. Therefore \( \Delta i_L = 2A \) is the maximum admissible value. Solving eq. (2) for \( L \) yields:

\[
L = \frac{(V_s - V_a) \cdot DT_s}{\Delta i_L}
\]

(3)

Where: \( T_s = \frac{1}{f_s} \)

Substitute eq.(1) in eq.(3), gives:

\[
L = \frac{V_s (1-D) DT_s}{\Delta i_L}
\]

(4)
 Clearly the maximum value of the right hand side of eq. (4) occurs at \( D = 0.5 \), thus the value of the inductor becomes:

\[
L = \frac{V_s T_s}{4 \Delta i_L}
\]  

(5)

Taking \( \Delta i_L = 2A \), the value of the inductor will be \( 1.5\, mH \).

**Capacitor Design:**
The output voltage ripple can be minimized by making the corner frequency \( f_c \) of the output LC filter such that \( f_c << f_s \), also a rule of thumb of \( 300\, \mu F / A \) minimum at \( 20\, kHz \) is more realistic when electrolytic capacitors are used[Chyrysis 89]; accordingly for the 8.2A rated armature current, the capacitor selected to be \( 3300\, \mu F \).

**Converter Model:**
The averaged state space equations for the buck converter are [Chrip 07]:

\[
\frac{\partial i_L}{\partial t} = \frac{1}{L} (d.v_c - i_L R - v_o)
\]  

(6)

\[
\frac{\partial v_c}{\partial t} = \frac{1}{C} (i_L - i_o)
\]  

(7)

\[
v_o = v_c + R_{esr} (i_L - i_o)
\]  

(8)

Where:
- \( d = 1 \) When the switch is on.
- \( d = 0 \) When the switch is off.

The converter matlab-simulink is shown in Fig.2 where the converter is controlled using pulse width modulation technique which its matlab-simulink is simply shown in Fig.3.

**III-DC motor Modeling and Simulation:**
The dc series motor is modeled by the equations below:

\[
v_a = e_g + (R_a + R_f)i_a + L_a \frac{\partial i_a}{\partial t} + L_f \frac{\partial i_a}{\partial t}
\]  

(10)

Where:
- \( e_g = K_a \Phi(i_a) \cdot n \)

\[
L_f = \frac{\partial \Psi}{\partial i_a} \approx \frac{\Psi(i_a + \Delta i_a) - \Psi(i_a)}{\Delta i_a} \text{ Where } \Delta i_a \approx 0
\]

The torque balance equation is:
\[ T_d = T_f + Bn + J \frac{\dot{n}}{\dot{t}} \]  

(11)

Where:

\[ T_d = Ka\Phi(i_a)i_a \]

\( E_g \) Versus \( I_a \) and \( \Psi_f \) versus \( I_a \) for the used motor are shown in table (1) [Sailendra 87]. These curves are interpolated with piecewise linear interpolation using the one dimension lookup tables of the matlab simulink library. These curves and motor parameters shown in the appendix are used in the matlab-simulink of the dc series motor as in Fig.4.

<table>
<thead>
<tr>
<th>( I_a ) in A</th>
<th>( \Psi_f ) in Wb-turn</th>
<th>( E_g ) in V at ( n_a = 1600 \text{ rpm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>5.0</td>
</tr>
<tr>
<td>1.0</td>
<td>0.115</td>
<td>22.25</td>
</tr>
<tr>
<td>2.0</td>
<td>0.28</td>
<td>35.0</td>
</tr>
<tr>
<td>3.0</td>
<td>0.415</td>
<td>52.5</td>
</tr>
<tr>
<td>4.0</td>
<td>0.54</td>
<td>67.0</td>
</tr>
<tr>
<td>5.0</td>
<td>0.665</td>
<td>79.0</td>
</tr>
<tr>
<td>6.0</td>
<td>0.76</td>
<td>88.5</td>
</tr>
<tr>
<td>7.0</td>
<td>0.82</td>
<td>95.5</td>
</tr>
<tr>
<td>8.0</td>
<td>0.88</td>
<td>102.0</td>
</tr>
<tr>
<td>9.0</td>
<td>0.94</td>
<td>106.5</td>
</tr>
<tr>
<td>10.0</td>
<td>0.99</td>
<td>108.5</td>
</tr>
</tbody>
</table>

**IV- Speed Computing Unit, PI controller, and Current Limiter:**

Using eq.(10) in terms of the average values, the motor speed can be computed as:

\[
  n = \frac{V_a - (R_a + R_f)I_a}{Ka\Phi(I_a)}
\]

(12)

\( Ka\Phi(I_a) \) is found from the one dimension lookup table (\( E_g \) versus \( I_a \)) after division the back emf by the motor speed (\( n_a \)) at which the motor back emf is measured. The output of this unit is passed through a low pass filter to remove or reduce the noise. The simulink of this unit is built as shown in Fig.5.
Using transient performance specification [Basilio 02], P-I controller is designed and tuned such that its transfer function is given by:

\[ K(S) = K_p \left(1 + \frac{1}{T_i S}\right) \]  \hspace{1cm} (13)

Where: \( K_p = 1.1 \) and \( T_i = 0.4 \text{Sec} \).

A current limiter is used to protect the system from the large starting and transient currents, which can be damage the converter and possibly the motor. Fig.6 and Fig.7 represent the simulink of the controller and the current limiter respectively.

V Simulation Results:
Based on the system model, the motor parameters, and the converter parameters shown in appendix, Simulink is used to simulate the system under consideration as shown in Fig.8. The dynamic performance of the drive system is evaluated through step disturbances in the desired speed, load torque, and converter input voltage. Fig.9 shows the transient response of the motor speed and current due to step increase and decrease in the desired speed (from 100 rad/sec to 200 rad/sec at t = 5 sec and from 200 rad/sec to 100 rad/sec at t = 10 sec), when the load torque is 2.5 N.m at rated converter input voltage. The motor attained its reference speed in about 2.5 sec. Fig.10 demonstrates the response due to step increase and decrease in the load torque (from 1.5 N.m to 3 N.m at t = 6 sec and from 3 N.m to 1.5 N.m at t = 10 sec), when the desired speed is 200 rad/sec at rated converter input voltage. The speed is restored to the reference value within 1.5 sec. Furthermore, the system is tested by step decrease and increase in the converter input voltage as shown in Fig.11 (from 240 V to 180 V at t = 5 sec and from 180 V to 240 V at t = 10 sec, when the load torque is 2.5 N.m and motor speed is 200 rad/Sec). The motor retained its reference speed within 2 sec. The three figures clarify the soft start of the motor and the operation of the current limiter.

VI Conclusion:
A dc series motor fed from buck converter with sensorless speed control is simulated taking the nonlinearity of the dc series motor in consideration and this will lead, to expected good coherency between the simulation and practical results if the system is implemented. Speed computation unit is used based on the measurement of the converter output voltage and current. The system simulation shows the effectiveness of this speed unit with satisfactory operation of the PI controller since the speed response has small overshoot, accepted rise time with nearly zero steady state error.

REFERENCES:


**APPENDIX:**

The dc series motor used has the following specifications:
DC series motor, 110V, 8.2-A, 2300 rpm, 0.9 Kw

\[ R_a + R_f = 2.32\Omega, \quad L_a = 25mH, \quad J = 0.025Kg - m^2, \quad B = 0.001N.m.sec/ rad. \]

The buck converter specifications are:
Input voltage \( V_s = 240V \).

Output voltage \( V_o = V_a \) is adjustable according to required speed and load.

Output current \( I_o = I_a = 8.2A \).

\( L = 1.5mH \), with internal resistance \( R_i = 0.017\Omega \), \( C = 3300 \mu F \), with \( R_{esr} = 0.05\Omega \), switching frequency \( f_s = 20KHz \).
Fig. 1 Sensorless dc series drive system
Fig. 2 Simulink of a buck converter
Armature voltage

Load torque

Motor torque

Fig. 4 Simulink of dc series motor
Fig. 5 Simulink of speed sensing unit

\( \text{no} = 167.55 \text{ rad/sec} \)
Fig. 6 Simulink of PI controller

Fig. 7 Simulink of current limiter.
**Fig. 8** Simulink of the overall system

**Load Torque**

- Input Voltage

**Saturation**

Step 3

Step 6

Step 5

Step

**AND**

Logical Operator

**PWM**

**Duty signal**

**Buck converter**

Armature voltage

Subsystem 2

n

Subsystem

DC Series Motor

**LPF**

**Current limit**

la

la

Step 5

Step 3

Step 2

Step 1

**PI Controller**

Speed error

Out 1 In 1

Subsystem 4

**Saturation**

**Control signal**

Step 6

Step

Step

**Load Torque**

- Input Voltage

**LPF**

**Speed Sensing Unit**

**Reference Speed**

Step 1

Step 2

**Saturation**

**Speed error**

Out 1 In 1

Subsystem 4

**PI Controller**

Step 1

Step 2
Fig. 9 Transient response due to step increase and decrease in speed

Fig. 10 Transient response due to step increase and decrease in load torque
Fig. 11 Transient response due to step increase and decrease in the input voltage